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An overview of the use of plants, polymers and nanoparticles as antibacterial materials

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ABSTRACT

The expansion of industry, climate change, deforestation, and pollution of oceans, and exponential increase in the multidrug-resistant bacteria, humans are more to danger than ever before. In recent years, humans have been affected more than ever by bacterial and fungal infections and even mosquito-related diseases such as *lymphatic filariasis*, malaria, and cellulitis. For example, *Candida albicans* and *Aspergillus fumigatus* can cause invasive fungal infections in any organ of humans, and their resistance to antibiotics is increasing. For a long period of time, plant components have been used for curing the various ailments. Herbs were the basis of medicine in the past and also are extensively used in some countries such as China and India. The study of antimicrobial effects of plants is increasing continuously, which is due to the presence of diverse levels of their bioactive compounds. Humans are so interested in using natural antibacterial compounds like plant extracts and spices because they have their own characteristic flavor. Plants are useful for supporting human health and some parts of the plant (flowers, leaves, stems, and roots) have medicinal activities such as analgesics, antispasmodics, antimicrobials. With recent advances, in addition to plants, polymers and nanoparticles have come to the help of medical cures. Polymers and nanoparticles due to their unique properties, can be used in a variety of fields such as prosthesis, antibacterial and antifungal surfaces, drug carrier, gene delivery, cancer diagnosis, colorimetric detection of cancer cells, and cancer imaging. In this study, researches on plants, polymers, and nanoparticles antibacterial are reviewed.

1. Introduction

After the exploration of penicillin and its introduction into clinical use, it revolutionized the treatment of infections caused by bacteria, but during the time, one of the biggest recent global public health challenges is bacterial and fungal infections [1,2]. The high resistance of many gram-positive and gram-negative bacteria as well as fungi is relatively worrying issue, which can be intrinsic, adaptive or acquired feature [3-6]. Totally, bacteria have a social life and can communicate with each other through signaling molecules and adapt their behavior at the population level, which has been proven in both gram-positive and gram-negative bacteria [7]. Researches have shown that more than a billion people worldwide suffer from fungal infections each year, and over 1.6 million related deaths are being reported each year [8,9]. Among these, one of the most common causes of deadly fungal infections is *Aspergillus*, which despite significant advances in diagnosis and treatment, severe fungal diseases continues to be reported with high mortality, especially in immunocompromised patients with invasive infections [10]. In recent years, some multidrug-resistant

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∗ Corresponding author. Tel.: +989211868265; e-mail: mi_sheydaei@sut.ac.ir, m.sheydaei@yahoo.com gram-positive bacteria, including *Staphylococcus aureus*, *Streptococcus pneumoniae*, and *Enterococci*, have raised public health concerns [11,12]. Also, infections caused by gram-negative bacteria become much harder to treat due to the very high resistance to the drugs [13-15]. Additively, research shows that approximately two-thirds of deaths due to antibiotic-resistant bacteria in Europe are due to gram-negative infections [16]. Concerns about infections are greater in environments with high population densities [17]. Hospital environments are a major candidate for the cyclical transmission of viruses, bacteria, and fungi through patient-healthcare worker-surface contact [18-20]. Also, Transmission can occur through benchtops, telephones, toilets, food trays, and implanted medical equipment [21-23]. In addition to hospital environments, subway and bus stations are also at high risk of transmitting bacteria and fungi. Extensive efforts have always been made to prevent and treat fungal and bacterial infections, which are reflected by the continued development of antibiotics such as amphotericin B, azoles, hydrogels, silver particles, antimicrobial peptides, and plant-based antimicrobials [24-32]. Bacterial and fungal infections are always remarkable threats to health [33]. Over the years in the advancement of science has been one of the greatest achievements of antimicrobial materials because they can be used in different fields such as medical equipment, food packaging and storage, water treatment systems, and hospitals [34]. Among these, plants, polymers, and nanoparticles have some particular places [35,36]. This study is a review of research conducted in these three areas.

2. Antibacterial materials

2.1. Plants

Humans have been using plants as a source of medicine for thousands of years. Medicinal plants contain various biological compounds with anticancer, antibacterial, antifungal and etc. activities that can be used as drugs (Figure 1). Since the cost of producing synthetic drugs is so high, herbs can be an important alternative item, especially for developing countries and low-income countries. It is assessed that around 50,000 plant species have been studied and used for medical properties [37]. Okla et al. [38] investigated the antimicrobial properties of *avicennia marina* (forssk.) vierh. The results showed that the chloroform extract of roots of the *avicennia marina* exhibited inhibitory effects against both *Staphylococcus aureus* (minimum inhibitory concentration (MIC) = 1.5 mg/mL) and *Escherichia coli* (MIC = 1.7 mg/mL). Also, the ethanolic extract has shown antibacterial activity against *Pseudomonas aeruginosa* (MIC = 10.8 mg/mL), *Bacillus subtilis* (MIC = 6.1 mg/mL), *Staphylococcus aureus* (MIC = 2.3 mg/mL), and *Escherichia coli* (MIC = 6.3 mg/mL). Moreover, the leaf extract of the *avicennia marina* in ethyl acetate has shown antibacterial activity against against *Staphylococcus aureus* and *Escherichia coli* and ethanolic extract of the *avicennia marina* fruits has shown an inhibitory effect on the growth of *Aspergillus fumigatus* and *Candida albicans*.

Figure 1. Some plants with antibacterial properties.

Edraki et al. [39] investigated the antibacterial properties of Matcha green tea. The results of antibacterial tests showed that Matcha has the ability to inhibit *Escherichia coli*, *Pseudomonas aeruginosa*, *Salmonella paratyphi-A serotype*, *Shigella dysenteriae*, *Bacillus subtilis*, *Staphylococcus aureus*, *Staphylococcus epidermidis*, *Streptococcus pyogenes*, and *Candida albicans*, but has no effect on the *Aspergillus niger*. According to the results, the maximum and minimum inhibition zones created by Matcha belonged to *Pseudomonas aeruginosa* and *Escherichia coli*, respectively. Ili´c et al. [40] investigated the antioxidant and antimicrobial properties of goji berries. Based on the results, red goji berry had the highest content of fats, dietary fiber, iron, total carotenoids, and 2-*O*-β-ᴅ-glucopyranosyl-ʟ-ascorbic acid. But, the yellow goji berry extract showed the highest level of flavonoids and the best antimicrobial properties. Also, the highest total phenolic content and the most potent antioxidant activity were for the extract of black goji berry. Bendjedid et al. [41] investigated the antioxidant, antimicrobial, photoprotective activities and cytotoxic effect of leaves extracts and fractions of *Aloe vera*. The results have shown that yields of methanol, chloroform, ethyl acetate, n-butanol, aqueous, acetone extracts are respectively 20.56%, 3.4%, 1.58 %, 14.1 6%, 13.56%, and 0.68 %. Also, the n-butanol fraction on acetone and methanol extracts has positive effect against all the bacteria. The antioxidant activity showed that the chloroform fraction exhibited highest activity in (OH$^{\bullet 2}$) scavenging assay and in galvinoxyl radical scavenging assay, the acetone extract exhibited highest activity in phenanthroline assay. Moreover, the all extracts and fractions showed high photoprotective activity, and acetone, chloroform, and ethyl acetate fractions have displayed significant effect against the brine shrimp larvae. Furthermore, the highest toxicity was related to acetone extract and ethyl acetate fraction.

Figure 2. The important antibacterial compounds in Matcha.

Danish et al. [42] investigated the antimicrobial and antifungal properties of *Aloe vera*. *Escherichia coli* and *Agrobacterium tumefacins* showed zone of inhibition around 18 mm, and *Bacillus subtitis* and *Bacillus megaterium* showed around 16 mm, and Also *Proteus mirabilis* and *Pseudomonas aeruginosa* showed minimum zone of inhibition which is around 11 mm, too. Increasingly, among all used fungal strains *fuserium oxysporum* and *Aspergillus niger* showed excellent results around 19 mm both against root extract and leaves extract. Alamholo [43] investigated the chemical composition, antibacterial and antioxidant activity of *Thymus daenensis* and *Thymus eriocalyx* essential oils. The results showed that eleven (94.06%) and seven (90.76%) compounds were presented in *Thymus eriocalyx* and *Thymus daenensis* essential oils, respectively. *Thymus eriocalyx* essential oil showed the highest activity against *Bacillus cereus*. The most potent radical scavenging activity was also obtained for *Thymus daenensis* essential oil. Moreover, *Pseudomonas aeruginosa* and *Staphylococcus aureus* showed the highest susceptibility against *Thymus eriocalyx* essential oil. Furthermore, gram-negative bacteria showed resistance to *Thymus daenensis* essential oil. Sadat et al. [44] investigated the antimicrobial activity of *Matricaria chamomilla*, *Malva sylvestris*, and *Capsella bursa-pastoris* against methicillin-resistant *Staphylococcus aureus*. For this purpose, the plants thoroughly dried in the shade and after grinding, extraction was performed by the maceration method and the extract was dried at 37 °C for 24 h. The results showed no inhibitory effects for the ethanolic extracts of *Malva sylvestris* and *Capsella bursa-pastoris* against the *Methicillin-resistant Staphylococcus aureus* isolates. But the chamomile flower and leaves extract showed antibacterial activity. Rubab et al. [45] investigated the preservative effect of Chinese cabbage (*Brassica rapa subsp. pekinensis*) extract on their molecular docking, antioxidant and antimicrobial properties. The results expressed that the ethanol, methanol, and distilled water extracts were not effective at all. Also, the chloroform extract was the most effective among all extracts in retarding microbial growth. Biochemical results revealed that total phenol and flavonoids were higher in the extracts of *Brassica rapa subsp. pekinensis*, which resulted in enhanced antioxidant activity in chloroform extracts. The results showed that mid-polar extracts of *Brassica rapa subsp. pekinensis* were a potential source of polyphenols with significant antimicrobial activity.

Karthik et al. [46] investigated the larvicidal, super hydrophobic, and antibacterial properties of herbal nanoparticles from *Acalypha indica*. The nanoparticles were prepared using the ball-milling technique. The nanoparticles possess an average particle size distribution of 54 nm and are superhydrophobic in nature. The maximum zone of inhibition was observed against *Escherichia coli* and *Staphylococcus aureus* at a concentration of 100 mg mL^{-1}. Also, Mosquito repellent properties were investigated against three disease vectors, *Aedes aegypti*, *Anopheles stephensi* and *Culex quinquefasciatus*, and showed important larvicidal activity. The acute toxicity of the herbal nanoparticles was tested with an in vivo animal model, zebrafish and it was determined that the particles of 200 mg L^{-1} concentration were highly effective with no mortality of the zebrafish embryos. Subramani et al. [47] investigated the antibacterial and textural properties of cotton fabrics using nanoparticles from *Azadirachta indica* (neem). Nanoparticles were prepared from shade-dried leaves using ball milling, and then nanoparticles-chitosan nanocomposites were prepared and coated on cotton fabrics. The average particle size diameters of the nanoparticles were around 30 nm, and also the topography of the fibers was coated by nanoparticles and chitosan polymer was observed to be rough. The antibacterial results showed that the agar loaded with nanoparticles had the maximum zone of inhibition against *Escherichia coli* and *Staphylococcus aureus* bacteria at a concentration of 100 mg ml^{-1}.

2.2. Polymers

One of the biggest achievements of science has been antimicrobial materials, because they can be used in various fields. Among these, antimicrobial polymers are one of the suitable candidates because they have intrinsic properties such as high resistance to solvents, corrosion, moisture (Figure 3) [48,49]. Polymer materials with strong bactericidal properties through directly grafting quaternary ammonium group, nanoparticles, plant extracts, etc. are used because of their excellent mechanical properties, low cost, and popularity [48]. The surface of the antibacterial polymer must have self-cleaning properties that can maintain its antibacterial properties for a long term [48,49]. Sheydaei et al. [50] prepared a nanocomposite containing polyvinyl chloride modified using sodium trisulfide (PVCS) as a matrix and graphene oxide (GO) and investigated antibacterial and mechanical properties. The antibacterial activity of the samples were investigated against *Bacillus subtilis*, *Staphylococcus aureus*, *Escherichia coli*, and *Shigella dysenteriae*. Due to the presence of sulfur, the polymer showed antimicrobial properties and was inhibitory and killing against the studied bacteria. Mechanical and antimicrobial properties were also enhanced by adding GO to the matrix.

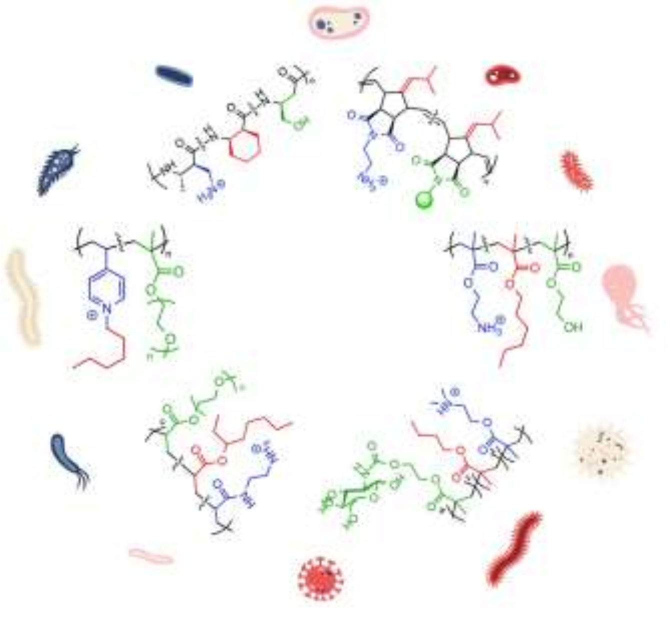

Figure 3. Some polymers with antibacterial properties.

Sun et al. [51] prepared the polypyridinium salt coated silica nanoparticles and investigated antibacterial properties. For this purpose, bare silica particle carriers with different particle sizes (SiO_2-1 (15 ± 5 nm), SiO_2-2 (30 ± 5 nm), and SiO_2-3 (2 mm)) and functional organic-inorganic silica particles (SiO_2-2/P4VP-psl) “grafted” by P4VP-psl (4-vinyl pyridine-polypyridinium salt) and then, antibacterial ability was evaluated against *Escherichia coli*. The average size of SiO_2-2/P4VP-psl was 161.3 nm. Also, the results showed that silica particle sizes had no effects on its antibacterial and antifouling activities, but SiO_2-2/P4VP-psl possessed more excellent antibacterial and antifouling ability than other bare silica particle carriers. Moreover, the main role in killing bacterial cells and renewing the antibacterial ability of positive and negative charges in pyridinium salts outside SiO_2-2/P4VP-psl. Li et al. [52] prepared a polyvinyl alcohol/polyacrylamide interpenetrating networks (PVA/PAAm IPN) hydrogel and investigated antibacterial and mechanical properties. Hydrogel was prepared by a one-pot free radical polymerization method and the antibacterial activity of the hydrogel was investigated against *Escherichia coli* and *Staphylococcus aureus*. Also, polyhexamethylene guanidine (PHMG) was used as an antibacterial agent. The PVA/PAAm IPN hydrogel without PHMG has a weak inhibitory effect on gram-positive and gram-negative bacteria, But as the concentration of PHMG increases, the inhibition zone increases. The results of cytotoxicity of PVA/PAAm IPN hydrogel showed that approximately 90% of cell viability can be observed at concentrations less than 5 mg.ml^{-1}. Additively, hydrogels have excellent adhesion to substrates such as rubber, wood, leather, plastic, stone, Teflon, glass, copper, ceramics and other materials.

Zhu et al. [53] prepared an antibacterial ultrafiltration membrane with silver (Ag) nanoparticle impregnation. This membrane was prepared by interfacial polymerization method and the membrane surface was made of commercial polyethersulfone (PES), and also the antibacterial activity of the membrane was investigated against *Escherichia coli*, *Vibrio coralliilyticus*, *Exiguobacterium aestuarii*, and *Staphylococcus aureus*. Using sodium borohydride in the presence of polyethyleneimine (PEI), Ag nanoparticles were prepared from the reduction of silver nitrate ($AgNO_3$). The results showed that the membrane needed more time to completely kill gram-positive bacteria than gram-negative bacteria, and also the membrane prepared with 50 mmol/L of $AgNO_3$ and 20 mmol/L of PEI had the better antibacterial effect against *Escherichia coli*, and at $AgNO_3$ concentration of 50 mmol/L, the sizes of the Ag nanoparticles are in the range of 8 to 75 nm. Moreover, this membrane was 100% effective in killing various types of marine bacteria and bacteria in the seawater Sentosa Island in Singapore. Tekin et al. [54] prepared a bionanocomposites of organo-sepiolite/chitosan/silver. The samples with various content of Ag were prepared via synthesis of Ag nanoparticles using the wet chemical reduction method in the lamellar space layer of the organo-sepiolite/chitosan (O-SEP/CS), and sodium borohydride was used as the chemical reduction agent. The scanning electron microscope (SEM) images of the SEP and O-SEP showed fibrous structures, but the O-SEP had more individual fibrous particles after the modification, and also the CS showed homogenous, dense, and smooth surface structures, while the O-SEP/CS composite showed a rough morphology with many protruding bulk-like agglomerates. The results showed that the bionanocomposites were sensitive to bacteria and for all tested bacteria had high antibacterial activity, but the antimicrobial activity against gram-negative bacteria is higher than against gram-positive bacteria, and also increased when the amount of Ag nanoparticles in synthesized composites had grown. Solak et al. [55] prepared mupirocin-loaded microspheres were embedded in the ethyl cellulose films, and release controlling of the mupirocin against *Staphylococcus aureus* was investigated. For this purpose, polyvinyl alcohol and sodium alginate were used and the microspheres were prepared by the emulsion cross-linking method and cross-linked with calcium chloride and finally, the microspheres were covered with ethyl cellulose. The SEM images showed that the microspheres have maintained a spherical form. The results showed that increasing of the amount of polyvinyl alcohol will add the % encapsulation efficiency and % drug loading. Also, microspheres showed antibacterial activity similar to mupirocin and the amount of active substance released in a controlled manner.

Tekin et al. [56] investigated the thermal, photocatalytic, and antibacterial properties of calcinated nano-titanium dioxide (TiO_2)/polymer composites. Polyethylene glycol (PEG) and polyvinyl alcohol (PVA) were used for the matrix, and also TiO_2 nanoparticles, PEG/TiO_2, and PVA/TiO_2 were synthesized using sol-gel method. The photocatalytic and antibacterial activities of samples were investigated using Acid Black I dye and *Escherichia coli*, respectively. The SEM images showed that TiO_2 nanoparticles had a spherical shape and a porous structure and their average diameter was approximately 15 nm. Also, due to the dispersion of TiO_2 particles on the PVA matrix, the surface morphology of the PVA/TiO_2 composite is uniform. But, the surface morphology of the PEG/TiO_2 composite had pores, which is due to the molecular weight of PEG, and due to the compatibility of TiO_2 particles with PEG, the structure of the PEG/TiO_2 composite showed a homogeneous distribution. Antibacterial results showed that TiO_2 particles, PVA/TiO_2, and PEG/TiO_2 removal 19.9%, 24.4%, and 26.2% of bacteria, respectively. Also, the investigation of photocatalytic aspect showed PEG/TiO_2 composite showed better activity compared to other samples and the dye decomposition of the PEG/TiO_2 composite is 62.82%. Khona et al. [57] prepared a Hyperbranched polymer nanofibrous membrane grafted with silver nanoparticles for dual antifouling and antibacterial properties. For this purpose, Ag-loaded hyperbranched polyethyleneimine / polyethersulfone nanofibrous membranes were prepared via electrospinning. The SEM images revealed smooth, dense, and uniform nanofibres with average diameters ranging from 107.8 ± 46.2 to 145.9 ± 49.9 nm, and also Ag nanoparticles were observed in a spherical shape with an average diameter of 6.3 ± 2.3 nm. The antibacterial results showed that the membranes displayed excellent antibacterial properties against *Escherichia coli*, *Staphylococcus aureus* and *Pseudomonas aeruginosa* achieving an inhibition of growth rate (IR) ≥ 99%, and also prevented the attachment and colonisation of the three bacterial species that this is possibly due to the production of reactive oxygen species by Ag nanoparticles, which causes oxidative stress and the death of bacterial cells. Khaki et al. [58] prepared new thermostable polyamides containing xanthene units with modified GO nanoparticles. For this purpose, the first two series of new diamine monomers containing ether linkages, polar trifluoromethyl, and xanthene segments were prepared, and polymers synthesized through condensation polymerization. *Staphylococcus aureus* and *Pseudomonas aeruginosa* were used to investigate the antibacterial properties and *Aspergillus oryzae* and *Aspergillus Niger* were used to evaluate the antifungal activity. Thermogravimetric analysis results showed that polyamides have high thermal stability and their glass transition temperatures within the range of 187-244 ºC, and also 10% weight loss temperatures within the range of 395-497 ºC. The antibacterial results that due to the presence of xanthene segments in the structure as well as the presence of GO, the samples have good antibacterial activity.

2.3. Nanoparticles

In following years, ongoing research has focused on the use of nanoparticles as effective as antimicrobial therapies. Nanoparticles due to their unique properties, have many applications in medical imaging, drug delivery, and nanocomposites [59-65]. Also, particles can be used as carriers due to their unique structures such as tubular, plate and etc. (Figure 4).

Figure 4. SEM images of (a) nano clay, (b) graphite, (c) carbon nanotube.

Sethy et al. [66] studied the antibacterial behavior of polyacrylic acid/GO/silver nanocomposites with various percentages of silver nanoparticles (9×10^{-3} up 27×10^{-3} *wt.*%) are checked against *Escherichia coli* bacteria. The results showed an inhibition zone for *Escherichia coli* between 12-17 mm with various *wt.*% of silver nanoparticles. Also, the results of Factori et al. [67] that studied the antibacterial behavior of poly (vinyl alcohol)/zinc oxide (ZnO) nanocomposites against *Escherichia coli* and *Staphylococcus aureus* showed that up to 5 *wt.*% of zinc oxide can be an inhibition zone with a diameter of 10-13 and 10-14 mm for *Escherichia coli* and *Staphylococcus aureus*, respectively. Results of Hassanin et al. [68] that studied the antibacterial behavior of starch/copper nanocomposites with a constant percentage of copper nanoparticles (one hundred milliliters of 1 mM of copper nanoparticles solution) against *Escherichia coli* and *Bacillus subtilis* showed that MIC for *Escherichia coli* and *Bacillus subtilis* are 125 and 7.81 µg/mL. Al mogbel et al. [69] studied the antibacterial behavior of poly(vinyl pyrrolidone)/chitosan incorporated by GO *via* laser ablation. The inhibition zone of pure poly(vinyl pyrrolidone)/chitosan against *Escherichia coli*, *Staphylococcus aureus*, and *Bacillus subtilis* were 5 ± 0.98, 7 ± 0.73, and 4 ± 0.89 mm, respectively. But, after two times of laser ablation (5 and 10 min), and added GO in the structure, antimicrobial activity enhancement in the inhibition zones. First, after 5 min of laser ablation, inhibition zones increased to 10 ± 0.34 for *Escherichia coli*, to 12 ± 0.04 for *Staphylococcus aureus*, and to 11 ± 0.46 for *Bacillus subtilis*. Then, after 10 min of laser ablation, again inhibition zones increased to 13 ± 0.72 for *Escherichia coli*, to 17 ± 0.26 for *Staphylococcus aureus*, and to 15 ± 0.7 for *Bacillus subtilis*.

Edraki et al. [24] introduced ginger particles into the structure of sodium montmorillonite nano clay. The results showed that ginger particles could be placed between the layers as well as slightly on the surface. Also, the results of antibacterial test showed that this hybrid inhibits *Escherichia coli*, *Pseudomonas aeruginosa*, *Salmonella paratyphi-A serotype*, *Shigella dysenteriae*, *Bacillus subtilis*, *Staphylococcus aureus*, *Staphylococcus epidermidis*, *Streptococcus pyogenes*, and *Candida Albicans*. But it had no effects on the *Aspergillus niger*. Additively, the results showed that this hybrid had more effect on gram-negative bacteria. Suleiman et al. [70] investigated the antibacterial properties of sulfur nanoparticles prepared used sodium thiosulphate and tetraoctylammonium bromide surfactants in conc by precipitation method. The results showed that the nanoparticles had antimicrobial activity against *Staphylococcus aureus* but there was no antimicrobial activity against *Escherichia coli* and *Pseudomonas aeruginosa* at 0.68 to 800 µg/mL. Sulfur exerts its effects through contact action, respiratory inhibition, and the formation of chelating complexes with cellular lipid moieties, in fact, after taking up of sulfur by pathogens, it forms hydrogen sulfide and disrupts important intermediary metabolites in the mitochondria [71].

Figure 5. The antibacterial compounds in ginger.

Priyadarshi et al. [72] investigated the enhanced functionality of green synthesized sulfur nanoparticles using kiwifruit peel polyphenols. They used kiwifruit peel polyphenols as natural capping agents to cap sulfur nanoparticles. This was done to address the hydrophobicity of sulfur nanoparticles and the low stability of aqueous suspensions, and the antimicrobial activity of both kinds of nanoparticles was studied against *Listeria monocytogenes* and *Escherichia coli*. The results showed the capped particles and uncapped particles were 90 and 130 nm, respectively, and capped particles had better dispersion and stability in aqueous suspension. Also, the antimicrobial activity of sulfur nanoparticles increased by 2 times, indicating that the function of sulfur nanoparticles was improved through capping. Both sulfur nanoparticles were not effective against *Escherichia coli* and no inhibition zones were observed, but inhibition zones were observed against *Listeria monocytogenes*, that is probably due to the difference in the cell wall structure of the two types of bacteria, In fact, sulfur nanoparticles can penetrate more easily inside the gram-positive bacterial cell, compared to gram-negative, and exert antimicrobial effect more proficiently. Moreover, thermal analysis results showed degradation of capped particles at a much lower temperature than uncapped particles, which is due to the decomposition of organic kiwi fruit peel polyphenols before sulfur nanoparticles. Abed et al. [73] synthesized iron oxide nanoparticles by mixing chilli with rust iron extract and investigated antibacterial activity. Iron oxide nanoparticles were synthesized *via* a chemical reaction by mixing hot red pepper with waste rust iron extract at 300 °C for 1.5 h. The results showed the particle sizes ranged from 27.59 to 29.29 nm with cubic structures. The nanoparticles yielded a high level of inhibition against bacterial activity, which is mainly due to the iron releasing most of the metal ions inside of it, which all attach to the bacterial cell wall due to electrostatic attraction. Also, metal ions both interact with the surface of the membrane and can penetrate inside bacteria. Moreover, the effect of nanoparticles was more for gram-positive bacteria than gram-negative bacteria.

Figure 6. The most important antibacterial compounds in red hot chili pepper.

Garibo et al. [74] synthesized Ag nanoparticles using *Lysiloma acapulcensis* and investigated antibacterial activity. The presence of alkyl halides and other reducing agents in the extract of *Lysiloma acapulcensis* can reduce Ag to Ag nanoparticles and enhance its antimicrobial activity. Nanoparticles size ranged of 1.2-62 nm with an average size of 5 nm with spherical and quasi-spherical structures. The Nanoparticles showed a significant antimicrobial effect against *Candida albicans*, *Escherichia Coli*, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*, that the antimicrobial potency obtained was as follows: *Escherichia Coli* ≥ *Staphylococcus aureus* ≥ *Pseudomonas aeruginosa* > *Candida albicans*. Also, the results showed that these Ag nanoparticles have higher antimicrobial potency than chemically produced Ag nanoparticles and also low-cytotoxicity than the Ag nanoparticles produced chemically. Azizi-Lalabadi et al. [75] investigated the antimicrobial activity of titanium dioxide and zinc oxide nanoparticles which were supported in 4A zeolite. The presence of titanium dioxide and zinc oxide nanoparticles in 4A zeolite caused to control the release of them, and enhance their antimicrobial properties. The results showed the numbers of viable bacterial cells of *Staphylococcus aureus*, *Pseudomonas fluorescens*, *Listeria monocytogenes*, and *Escherichia coli* decreased significantly. In fact, the most sensitive bacteria were *Pseudomonas fluorescens* and then *Escherichia coli*. Kaushik et al. [76] investigated the antimicrobial activity and wound healing potential of ZnO nanoparticles. The results showed that average particle size increases due to annealing, accordingly for ZnO nanoparticles annealed at 300, 500, 700, and 900°C, particle sizes 82 nm, 150 nm, 230 nm, and 420 nm, respectively. Also, nanoparticles are spherical and mono dispersive in nature. Moreover, the growth of fibroblast cell is higher with nanoparticles of larger particle size, and also antimicrobial activity is higher for nanoparticles of lower particle size. The nanoparticles inhibits both gram-positive, gram-negative bacteria, and fungus. Liu et al. [77] investigated the antimicrobial activity of graphite, graphite oxide, graphene oxide, and reduced graphene oxide. The antibacterial activity of the nanoparticles was investigated against *Escherichia coli*. The results showed that graphene oxide has the highest antibacterial activities, followed by reduced graphene oxide, graphite, and graphite oxide. Direct contacts with graphene nanosheets disrupt cell membrane. In fact, there is a three-step antimicrobial mechanism for graphene-based materials that includes initial cell deposition on graphene-based materials, membrane stress caused by direct contact with sharp nanosheets, and the ensuing superoxide anion-independent oxidation.

3. Conclusion

To sum up, we reviewed recent researches on antibacterial materials. The antibacterial plants are very diverse and contain various biologically active compounds. Accordingly, there is an urgent need to continue research to find important medicinal plants for the world and to investigate their potential for the discovery of antimicrobial drugs. On the other hand, amazing advances have been made in the field of antimicrobial polymers and nanoparticles and they can be used in the main cyclical transmission environments of bacteria and fungi. They can be used as wall flooring, benches and etc.

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